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Princeton University Observatory
Peyton Hall
Princeton, NJ 08544

INTERIM REPORT

The Universe at Moderate Redshift

NASA Grant NAG 5-2759

Covering the Period
July 1, 1995 through June 30, 1996

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Goddard Space Flight Center
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Prepared by: Renyue Cen
Research Astronomer

And: Jeremiah P. Ostriker
Principal Investigator

July 23, 1996

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J.P. Ostriker and R. Cen have computed, including a current state-of-the-art treatment of hydrodynamical processes, heating and cooling, a variety of cosmological models into the extreme nonlinear phase to enable comparisons with observations. The results for such a suite of currently interesting models are summarized and compared. First, we note the common, model independent results. All have a mean ($z = 0$) temperature of $10^{4.5} - 10^{5.5}$ K , set essentially by photoheating processes. Most gas is in one of two components: either at the photoheating floor $10^{4.5}$ K and primarily in low density regions or else shock heated to $10^5 - 10^6$ K and in regions of moderate overdensity (in caustics and near groups and clusters). It presents a major observational challenge to observationally detect this second, abundant component as it is neither an efficient radiator nor absorber. About 2% to 10% of the baryons cool and collapse into galaxies forming on caustics and migrating to clusters. About 1%-2% of baryons are in the very hot X-ray emitting gas near cluster cores, in good agreement with observations. These correspondances between the simulations and the real world imply that there is some significant truth to the underlying standard scenarios for the growth of structure. The differences among model predictions may help us find the path to the correct model. For COBE normalized models the most relevant differences concern epoch of structure formation. In the open variants having $\Omega = 0.3$, with or without a cosmological constant, structure formation on galactic scales is well advanced at redshift z=5, and reionization occurs early. But if observations require models for which most galaxy formation occurs more recently than $z = 2$, then the flat $\Omega = 1$ models are to be preferred. The velocity dispersion on the $1h^{-1}$Mpc scale also provides a strong discriminant with, as expected, the $\Omega = 1$ models giving a much higher (perhaps too high) a value for that statistic.

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J.P. Ostriker and collaborators successfully implemented the particle-particle/particle-mesh (P^3M) code on the special purpose hardware GRAPE. The code currently achieves a peak efficiency of one-third the speed of a vectorized P^3M code on a Cray C-90, and significant improvements are planned in the near future.

R. Cen, J.P. Ostriker and collaborators have investigated the nonlinear clustering of dark matter particles in an expanding universe using N-body simulations. One can gain some insight into this complex problem if simple relations between physical quantities in the linear and nonlinear regimes can be extracted from the results of N-body simulations. Hamilton et al. (1991) and Nityananda and Padmanabhan (1994) have made an attempt in this direction by relating the mean relative pair velocities to the mean correlation function in a useful manner. They investigate this relation and other closely related issues in detail for the case of six different power spectra: power laws with spectral indexes $n = -2, -1$, cold dark matter (CDM), and hot dark matter models with density parameter $\Omega = 1$; CDM including a cosmological constant (Λ) with $\Omega_{CDM} = 0.4$, $\Omega_\Lambda = 0.6$; and $n = -1$ model with $\Omega = 0.1$. They find that: (i) Power law spectra lead to self-similar evolution in an $\Omega = 1$ universe. (ii) Stable clustering does not hold in an $\Omega = 1$ universe to the extent our simulations can ascertain. (iii) Stable clustering is a better approximation in the case of $\Omega < 1$ universe in which structure formation freezes out at some low redshift. (iv) The relation between dimensionless pair velocity and the mean correlation function, $\bar{\xi}$, is only approximately independent of the shape of the power spectrum. At the nonlinear end, the asymptotic value of the dimensionless pair velocity decreases with increasing small scale power, because the stable clustering assumption is not universally true. (v) The relation between the evolved $\bar{\xi}$ and the linear regime $\bar{\xi}$ is also not universal but shows a weak spectrum dependence. They present simple theoretical arguments for these conclusions.

R. Cen, J.P. Ostriker and collaborators have described in detail a new method to trace light rays through an essentially three dimensional mass distribution up to high redshift. As an example, we apply this method here to a standard cold dark matter universe. We obtain a variety of results, some of them statistical in nature, others from rather detailed case studies of individual "lines of sight". Among the former are the frequency of multiply imaged quasars, the distribution of separation of the multiple quasars, and the redshift distribution of lenses: all that as a function of quasar redshift. We find effects from very weak lensing up to highly magnified multiple images of high redshift objects. Applied to extended sources, i.e. galaxies, this ranges from slight deformations of the shapes, only measurable in a big ensemble, through tangentially aligned arclets up to giant luminous arcs. We can study the weak coherent shear fields produced by lensing of large scale structure in directions that are devoid of large mass concentrations as well as the strong lensing around massive clusters of galaxies. Gravitational lensing directly measures mass density fluctuations along the line of sight to very distant objects. No assumptions need to be made concerning bias, the ratio of fluctuations in galaxy density to mass density. Hence lensing is a good tool to study the universe at medium and high redshifts. Cosmological models – normalized to the universe at redshift zero – differ considerably in their predictions for the mass distributions at these distance scales. Therefore lensing is a powerful tool to distinguish between various cosmological models. Our ultimate goal is to apply this method to a number of cosmogonic models in order to study their gravitational lensing effects and be able to eliminate some models whose properties are very different from the properties of the observed universe.

R. Cen, J.P. Ostriker and collaborators have examined effects of the weak gravitational lensing by large-scale structure on the determination of the cosmological deceleration parameter q_0. They find that the lensing induced dispersions on truly standard candles are 0.04 and 0.02 mag at redshift $z = 1$ and $z = 0.5$, respectively, in a COBE-normalized cold dark matter universe with $\Omega_0 = 0.40$, $\Lambda_0 = 0.6$, $H = 65$km/s/Mpc and $\sigma_8 = 0.79$. It is shown that one would observe $q_0 = -0.44^{+0.17}_{-0.05}$ and $q_0 = -0.45^{+0.10}_{-0.03}$ (the errorbars are 2σ limits) with standard candles with zero intrinsic dispersion at redshift $z = 1$ and $z = 0.5$, respectively, compared to the truth of $q_0 = -0.40$ in this case, i.e., a 10% error in q_0 will be made. A standard COBE normalized $\Omega_0 = 1$ CDM model would produce three times as much variance and a mixed (hot and cold) dark matter model would lead to an intermediate result. One unique signature of this dispersion effect is its non Gaussianity. Although the lensing induced dispersion at lower redshift is still significantly smaller than the currently best observed (total) dispersion of 0.12 mag in a sample of type Ia supernovae, selected with the multicolor light curve shape method, it becomes significant at higher redshift. They show that there is an optimal redshift, in the range $z \sim 0.5 - 2.0$ depending on the amplitude of the intrinsic dispersion of the standard candles, at which q_0 can be most accurately determined.

R. Cen and J.P. Ostriker, in collaboration with G.L. Bryan, M.L. Norman and J.M. Stone of University of Illinois, desribed a hybrid scheme for cosmological simulations that incorporates a Lagrangean particle-mesh (PM) algorithm to follow the collisionless matter with the higher order accurate piecewise parabolic method (PPM) to solver the equations of gas dynamics Both components interact through the gravitational potential, which requires the solution of Poisson's equation, here done by Fourier transforms. Due to the vast range of conditions that occur in cosmological flows (pressure difference of up to fourteen orders of magnitude), a number of additions and modifications to PPM were required to produce accurate results. These are described, as are a suite of cosmological tests.

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